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A PRESSURE IONIZATION CHAMBER FOR THE MEASUREMENT OF NEUTRON FLUXES AT TOLERANCE LEVEL IN PORTABLE INSTRUMENTS

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A. INTRODUCTION

The largest daily fast neutron dose considered safe for the human body ("tolerance dose") is taken to be 0.01 n units. If this dose is received during an 8 hour working day, the neutron flux has to be such as to provide an average dose rate of 0.01 n units per 8 hours. An instrument of high sensitivity is needed to measure fluxes of such order of magnitude in a reasonably short time and within a reasonably small space. High pressure ionization chambers as well as counters will serve the purpose. Which of the two should be chosen depends on what appears the most satisfactory compromise in fulfilling the following requirements:

1) The instrument should read as nearly proportional as possible to the biological effect, independently of the energy of the fast neutrons.

2) The instrument should have a high neutron to gamma sensitivity ratio, compared with the 100 r Victoreen chamber.

3) The instrument should be of rugged and simple construction and require no accessories that would make the total weight in excess of what is conveniently portable.

B. DISCUSSION OF REQUIREMENTS

1) To merely count neutrons is not sufficient. The instrument should "weigh" each neutron according to its energy, with a factor given by the dependence of biological effect on energy (this dependence is different for different biological objects). This eliminates Geiger point counters and Geiger-Mueller tube counters as possible choices. However, proportional counters or ionization chambers of suitable construction can be used. For a given type of tissue and a given type and quality of radiation, the amount of ionization per cm^3 of tissue is considered to be a reproducible measure of the biological effect. If one of the two types of instruments mentioned is lined with a substance, and filled with a gas, whose atomic compositions are similar to that of the tissue, and if the instrument is built according to some further conditions laid down by Gray (to be discussed in Section C), the ionization in the instrument will resemble that in the biological medium.

2) For a working day the accepted tolerance flux for gamma rays is 0.1 r. The 100 r Victoreen chamber on which the n unit is based has, therefore, a relative gamma to neutron sensitivity of 10 to 1 for the accepted tolerance fluxes. This factor of 10 is the result of two effects. For an equal amount of energy dissipated per cm^3 of tissue, the 100 r Victoreen chamber will record relative ionizations of about 1 to 2 for neutrons and gammas. One may say that it is twice as sensitive to gammas as it is to neutrons. On the other hand, the biological medium is, in general, more sensitive to fast neutrons than it is to gamma rays for equal energy dissipation per cm^3. This latter ratio is different for different effects. The lethal dose ratio (in ergs per cm^3) is about 5 to 1 for rats. The product of the factors 2 and 5 represents the ratio of 10 to 1 for the gamma and neutron readings of a Victoreen chamber, due to biologically equivalent doses.

The ideal instrument should have a relative neutron to gamma sensitivity 10 times as great as that of the Victoreen chamber. In that case, it could be calibrated simply in units of tolerance flux, regardless of the relative amounts of neutrons and gammas present. The proportional counter may again be useful. In order to produce a high relative neutron sensitivity, the proton content of gas and wall should be enriched. To reduce the gamma sensitivity, the wall could be made to absorb some of the gamma radiation.

3) As for ruggedness and simplicity, an ionization chamber connected to a single tube electrometer appears to be preferable to a counter circuit. Two types of portable electrometers have been constructed at Rochester, the low grid current type (FP54 or Victoreen tube No. VE 124 B) and the condenser-vane type. Inasmuch as these meters were ready and available, it was decided to construct the ionization chamber.

C. HYDROGEN CHAMBER

The reason for the higher biological efficiency of neutrons in most cases is probably to be found in the higher ion density ("specific ionization") along the tracks of the recoil nuclei (mostly protons). The higher the ion density in an ionization chamber, the higher will be the voltages necessary to collect all ions formed, as the recombination rate is proportional to the square of the ion concentration. For a given number of ions created, an ionization chamber will, therefore, read less and certainly never more, if the ions occur in dense clusters rather than being uniformly distributed. It follows that an ionization chamber cannot be made to take account of the factor of 5, mentioned in Section B (2), as long as one adheres to the conditions laid down by Gray which would insure compliance with the requirement discussed in Section B (1). These conditions are:

a) Wall and gas to resemble tissue in their atomic compositions.

b) Wall not thinner than longest range of ionizing particles in wall.

c) Gas gap not larger than shortest range of ionizing particles in gas.

The best one could do would be to modify the Victoreen chamber so as to fulfill the Gray conditions accurately for fast neutrons. In that case, the factor of 2, mentioned in Section B (2), would probably disappear, but such a chamber would still be five times more sensitive to gamma tolerance flux than it would be to neutron tolerance flux. Moreover, in order to be useful in a quick survey instrument, a chamber must have high absolute radiation sensitivity. This can be achieved by increasing pressure and simultaneously the collecting voltage. But this increase of the pressure would eventually lead to a violation of condition (c) unless the chamber dimensions are reduced, which would again reduce the absolute sensitivity. It seems, therefore, that in the present problem, the construction of a quick survey instrument of high sensitivity to fast neutrons, strict adherence to Gray's conditions has to be sacrificed in favor of sensitivity.

The principal agents causing ionization in the body tissue are the hydrogen nuclei and the electrons, the former being set in motion by fast neutrons, the latter by gamma rays. It occurred to Wollan and Landsverk* to look for a chamber gas which would contain protons and electrons in a ratio of five times that of body tissue. This factor of 5 would just compensate for the higher biological effectiveness of the neutrons. The atomic composition of the human body is as follows:

Element	Atomic number	% atoms
Hydrogen	1	62
Oxygen	8	25
Carbon	6	10.6

*Chicago Report CP-1930 (A-2815), pages 15–17, July 1944.

Element	Atomic number	% atoms
Nitrogen	7	1.2
Calcium	20	.33
Phosphorus	15	.22

The other elements contribute less than .2% of the atoms in the body. For each 62 protons there are, therefore, 62 x 1 + 25 x 8 + 10.6 x 6 + etc.... = about 345 electrons. The proton to electron ratio is as 62 to 345, or 1 to 5.6. A gas that is to contain five times this ratio must have protons and electrons in the proportion 5 to 5.6 or 1 to 1.1. Apparently hydrogen gas, with two protons and two electrons per molecule, comes very close to this.

Wollan and Landsverk filled a commercial steel high pressure cylinder of 6-inch height and 3-inch outside diameter with hydrogen and inserted an insulated collecting electrode. They were interested in measuring that neutron flux which would give the same reading on their electrometer, when connected to this chamber, as a gamma flux of tolerance intensity. They were also looking for a hydrogen pressure at which the absolute sensitivity of the instrument would be satisfactory and the relative sensitivity more or less independent of small pressure variations. Their report contains the information that a neutron flux of about 250 fast neutrons per cm^2 per second produces the same reading as gamma tolerance flux in the pressure range from 300 to 400 psi. On the other hand, it is believed that such a neutron flux releases an energy of about .025 roentgen equivalents per cm^3 of tissue in 8 hours. If that is multiplied by the factor 5, taking care of the high specific ionization in tissue, one finds that the chamber will read the same for gamma tolerance flux as it will for neutron flux producing 1.25 times the biological effect of gamma tolerance flux (.1 roentgen equivalent per cm^3 per 8 hours). Wollan and Landsverk's chamber thus appears to have a relative neutron to gamma sensitivity of 10 to 1.25 = 8 to 1, compared with the Victoreen chamber. This is not quite the ratio of 10 to 1, but it is close enough.

It would seem, however, that Wollan and Landsverk did not check on the strength of their neutron source with a Victoreen chamber, but accepted some other data concerning this information. Moreover, the source was quite weak and had to be brought so close to the pressure chamber that it became difficult to estimate the true average flux there (private information, courtesy of Mr. Landsverk). Hence, it was considered worth while by the present authors to collect extensive data on the relative neutron to gamma sensitivity of such an instrument, calibrating the neutron doses by means of a 100 r Victoreen chamber, upon which the definition of the "n" unit, and hence the accepted value for tolerance, is based.

D. SENSITIVITY MEASUREMENTS

1. Construction of Pressure Chamber

In order to insure good electric performance, the collecting electrode of the high pressure chamber should be brought out through a guard ring from which it is well insulated. Since it is difficult to accomplish this at the valve end of a commercial cylinder without interfering with tightness against gas leakage, it was decided to cut off the convex bottom of the steel cylinder (6-inch height, 3-inch OD, 1/8-inch wall thickness) and to replace it by a brass base plate upon which all the internal parts could be conveniently mounted. This brass plate acted also as a "guard ring." The outer chamber electrode consists of brass cloth, separated from the wall by a layer of 1/8-inch paraffin. Figure 3 shows the chamber in its present form (except for a slight modification of the polystyrene insulator, see Section E). The experimental model had no thread around the bottom of the steel cylinder. Instead there was a steel harness attached to the base plate which fitted over the neck of the cylinder. In this way, the chamber was capable of holding 600 psi without observable leakage over a period of several weeks.

2. Measurement of Neutron Doses

The neutron flux was produced in the cyclotron by 4.5 Mev deuterons on an external, water-cooled, lithium target. To cut down the gamma-ray background a lead wall of $1\frac{1}{2}$-inch thickness was erected covering the entire front of the cyclotron. Measurements with photographic films show that the gamma background is reduced to less than 2% by this wall. This means that out of 100 r units measured there, no more than 2 are due to gamma rays, the rest being due to neutrons. The relatively low biological effectiveness of gamma rays renders this residue quite negligible. The neutron doses had to be measured in terms of a 100 r Victoreen chamber. As the order of magnitude of the fluxes to be measured with the pressure chamber is 0.01 n/8 hours, it would take 8000 hours or about a year of continuous bombardment to produce a reading of 10 n units on the Victoreen chamber at the location where the pressure chamber is calibrated. For this reason, Victoreen chambers of higher sensitivity had to be compared with the 100 r chambers to serve as secondary standards. By placing a 25 r and a 100 r chamber side by side while running the cyclotron beam as high as possible, fairly reproducible readings were obtained after exposures of several hours each. For the neutron energy distribution prevailing behind the lead wall, it was found that the 25 r chamber reads the same as the 100 r chamber.

Next, a 0.25 r chamber and the 25 r chamber were compared in the same fashion. Since the full scale sensitivity ratio is now as 100 to 1, the 25 r chamber had to be exposed considerably longer than the 0.25 chamber. Care had to be taken that the cyclotron output was kept constant during these exposures. A sample result was as follows:

A 0.25 r chamber was exposed for 12 minutes at a given location (1 meter in front of the lead wall) while the cyclotron beam was kept at 27 cm (arbitrary galvanometer scale unit, corresponding to about 2 microamperes). It read 0.110 r.

Then a 25 r chamber was exposed for two hours at the same location and with the same cyclotron beam. It read 1.50 r. Since the latter was exposed ten times as long as the former, it was discharged at the rate of 0.15 r every 12 minutes. Now it was determined previously that the 25 r chamber reads true n units in this vicinity. Consequently, the correction factor, changing the 0.25 r chamber readings into n units is 0.150/.110 = 1.36. This factor holds only near the position 1 meter in front of the lead wall where all these data were taken. At more remote locations in the room, the neutron spectrum is different.

Due to scattering from floor, ceiling, walls, and objects in the room, the slow neutron component of the spectrum becomes more and more important as one moves away from the cyclotron. The 0.25 r chambers are rather sensitive to these slow neutrons. As they are much larger than the 100 r chambers, they have a smaller amount of surface per unit volume. Since the fast neutron recoils come mostly from the surface, this tends to reduce their sensitivity to fast neutrons. On the other hand, the large volume results in a large content of nitrogen. Slow neutrons produce protons from the volume nitrogen according to the reaction $N^{14}(n,p)C^{14}$.

If one determines the correction factor for a 0.25 r chamber farther back in the room, one obtains lower values. In the remote corner of the Rochester cyclotron room, a factor of 1.1 was obtained. This is due to the greater relative number of slow neutrons there, and the high slow neutron sensitivity of the 0.25 r chamber.

It may be noted here that a 0.25 r chamber can be made to read proportionally to a 100 r chamber by completely surrounding it with about 2 inches of paraffin. The paraffin prevents external slow neutrons from reaching the chamber. It also slows down the incoming fast neutrons to such a degree that the slow neutrons produced will create ionization in the chamber which is nearly proportional to the flux of external fast neutrons as measured by a 100 r chamber. It has been observed that this is true for such variations of neutron spectrum as occur within the cyclotron room. The correction factor of the 0.25 r chamber will thus become independent of the location in the room, provided the chamber is inserted in such a paraffin shield. At the location

just in front of the previously mentioned lead wall, the reading of a 0.25 r chamber is increased by a factor of 1.35 when surrounded by 2 inches of paraffin. Since this is just about equal to the correction factor (1.36) found previously, it may be said that the 0.25 r chamber used in these experiments (in fact two were used which always read the same within 2%) will read n units directly, if so shielded. This factor may, however, be different for other 0.25 r chambers. If the paraffin shield method is to be used elsewhere, the optimum paraffin thickness and the factor by which the paraffin shielded 0.25 r chamber readings have to be multiplied to give n units, should be redetermined. The optimum paraffin thickness can be found as follows:

Surround the 0.25 r chamber by increasingly thicker layers of paraffin. For a given exposure at a given location, the readings of the chamber will first increase, go through a maximum, and then decrease again. The paraffin thickness for which the maximum reading occurs is the optimum thickness. It will be found to be nearly independent of the location of the chamber in the room.

3. Neutron Sensitivity Versus Pressure

After evacuating and flushing with hydrogen, the chamber was filled with hydrogen to an initial pressure of 560 pounds above atmospheric and attached to a portable FP54 unit which was located 27 feet from the cyclotron lithium target. The deuteron beam current was adjusted such that the FP54 plate current meter drifted from 0 to 25 microamperes in 2 minutes. The total neutron dose received by the chamber in this time was monitored by a stationary integrator unit constructed at Rochester, a report on which has been submitted. After repeating this dose determination three times, some of the hydrogen was allowed to escape from the chamber. The new pressure was then measured, and three dose integrations were again performed, while the cyclotron beam was increased in such a manner as to let the FP54 current drift through the same interval as before, in the same time. This plate current change, and its rate, were kept constant throughout the experiment. Thus the number of ions collected, and the collection time were kept the same for all hydrogen pressures. The 4.5 Mev deuteron beam had to be varied between about .1 to .8 microampere, while the hydrogen pressure changed from the initial 560 pounds to the final 25 pounds above atmospheric. The results were as follows:

Hydrogen pressure (lb above atm)	Neutron dose needed to produce same ion collection during same time interval (arbitrary units)
560	2.71
465	2.79
365	2.96
250	3.22
200	3.41
150	3.83
100	4.69
75	5.34
50	7.04
25	10.98

The sensitivity of the chamber can be said to be inversely proportional to these doses. If one sets the sensitivity at 100 pounds equal to 480 (the reason for this choice of units is given in Section D (5)) one obtains the data as listed in Table 1.

Table 1.*

Pressure	Sensitivity to neutrons
25	205
50	320
75	422
100	480
150	586
200	663
250	702
365	759
465	807
560	831

* These data are plotted in curve No. 1 (Figure 1).

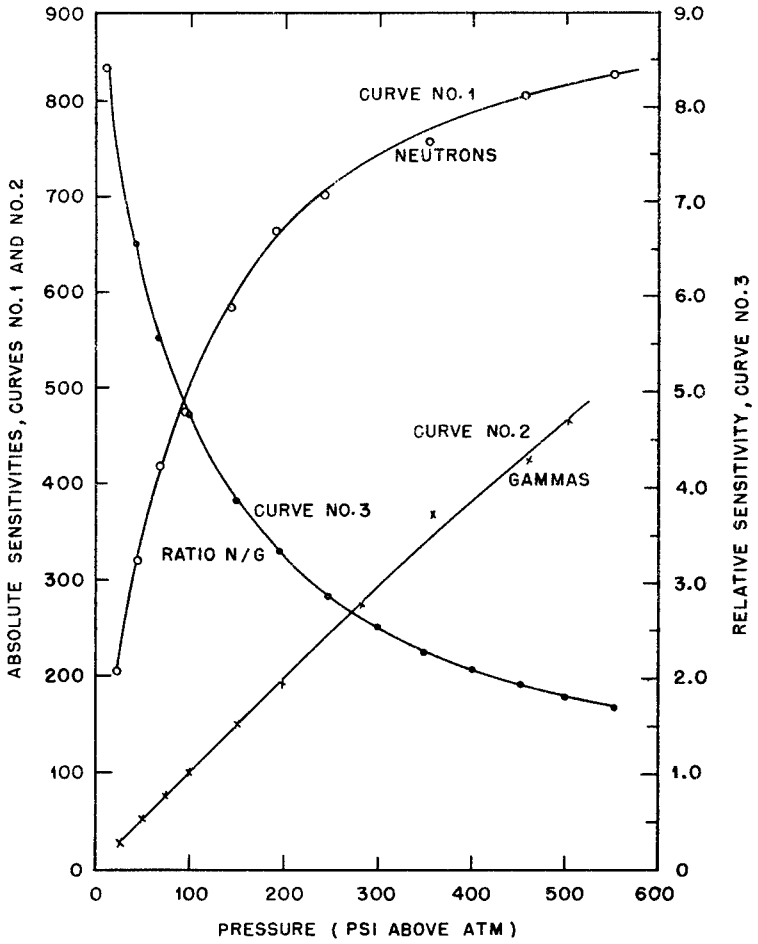

Figure 1

4. Gamma Sensitivity Versus Pressure

Two Ra capsules each containing 10 mg were available for these determinations. Again, total ion collection and collection time were held constant throughout the experiment. As discussed in Section D (3), the plate current meter was made to drift from 0 to 25 in 2 minutes by placing the Ra source(s) at the proper distance. As the pressure in the ionization chamber was reduced, this distance had to be decreased. The gamma radiation doses necessary to produce the standard FP54 reading are listed in the following tabulation:

Hydrogen pressure (psi above atm)	Gamma dose needed to produce standard ion collection at standard rate (micro-"r")
25	1170
50	610
75	400
100	305
150	205
200	155
285	111
365	82
465	72
510	65.5

The sensitivity of the chamber is inversely proportional to these doses. Setting the sensitivity at 100 psi equal to 100, the results are shown in Table 2.

Table 2.*

Pressure (psi)	Sensitivity to gammas (arbitrary units)
25	26
50	50
75	76
100	100
150	150
200	195
285	275
365	370
465	425
510	465

*These data are plotted in curve No. 2 (Figure 1).

5. Neutron-to-Gamma Sensitivity Ratio

This ratio was carefully determined at a chamber pressure of 100 psi above atmospheric of hydrogen. The neutron flux was measured as described in Section D (2), i.e., in "n" units per 8 hours. After each neutron reading the cyclotron was turned off, and the hydrogen chamber was placed near the Ra source, at such a distance as to produce the same reading (same ion collection at same rate). Since the gamma flux in "r" per 8 hours was known as a function of distance from the Ra source, the sensitivity ratio could thus be determined. The average value is 4.8 at 100 psi

above atm of hydrogen. The choice of 480 and 100 for the absolute sensitivities at this pressure discussed in Section D (3) and (4) is based on this value of 4.8. From curves 1 and 2, it is now possible to construct curve 3 which represents the dependence of sensitivity ratio upon pressure. The data in Table 3 were used in drawing curve 3 (Figure 1).

Table 3.

Hydrogen pressure (psi above atm)	Neutron-to-gamma sensitivity ratio
25	8.0
50	6.5
75	5.5
100	4.8
150	3.9
200	3.3
250	2.85
300	2.5
350	2.25
400	2.05
450	1.9
500	1.75
550	1.65

6. Sensitivity Versus Collecting Voltage

As the weight should be kept down, large batteries are not desirable in a portable instrument. Therefore, it is important to investigate whether there is reasonable constancy of the sensitivity for collecting voltage variations, even at low collecting voltages. Identical doses, as monitored by a separate FP54 integrator, were applied to the portable FP54 unit. For increasing values of the collecting voltage, the deflections of the plate current meter, caused by the fixed dose, showed a tendency to increase. However, there were voltage ranges, for which there was only a very slight change. Calibration of the plate current meter in terms of the grid voltage makes it possible to interpret the readings as a measure of chamber sensitivity. Two sets of data were taken: For hydrogen pressures of 100 pounds above atmospheric, and for 500 pounds. Making the sensitivity values found at 135 volts (arbitrarily) equal to 100, the data are shown in Table 4.

From the plot of the data in Table 4 (Figure 2), it can be seen that a sensitivity plateau is reached at 90 volts which extends to 150 volts, when the chamber pressure is 100 pounds. However, for 500 pounds pressure, no plateau is observed at such low voltages. Here, it was found that the sensitivity remains essentially constant between 700 and 900 volts.

E. DISCUSSION

1. Experimental Results

From curve 3, it is seen that the neutron-to-gamma sensitivity, starting at 8 for 25 pounds, falls rapidly with increasing pressure. The rate of decrease is reduced, however, so that the ratio becomes nearly constant (=1.8) at pressures of the order of 600 pounds. From Wollan and Landsverk's report one would conclude that the sensitivity ratio is about 8 to 10 in the pressure range from 150 to 400 pounds (with only 10% variation in this range), for they state that neutron fluxes of from 240 to 264 neutrons per cm^2 per sec give readings equal to those from gamma tolerance flux in this pressure range. The neutron tolerance flux is just about equal to that, namely 200 to 250 fast neutrons per cm^2 per sec.

Table 4. Chamber pressure.

100 lb		500 lb	
volts	sensitivity	volts	sensitivity
0	15.3	67.5	86.5
22.5	77	135	100
45	87.5	202.5	97.5
67.5	94	270	102.5
990	99.5	337.5	112
112.5	100	405	115
135	100	422.5	122
157.5	101	540	123
180	103	607.5	127
202.5	106	675	130
225	105	742.5	131
360	102	810	129
		900	129

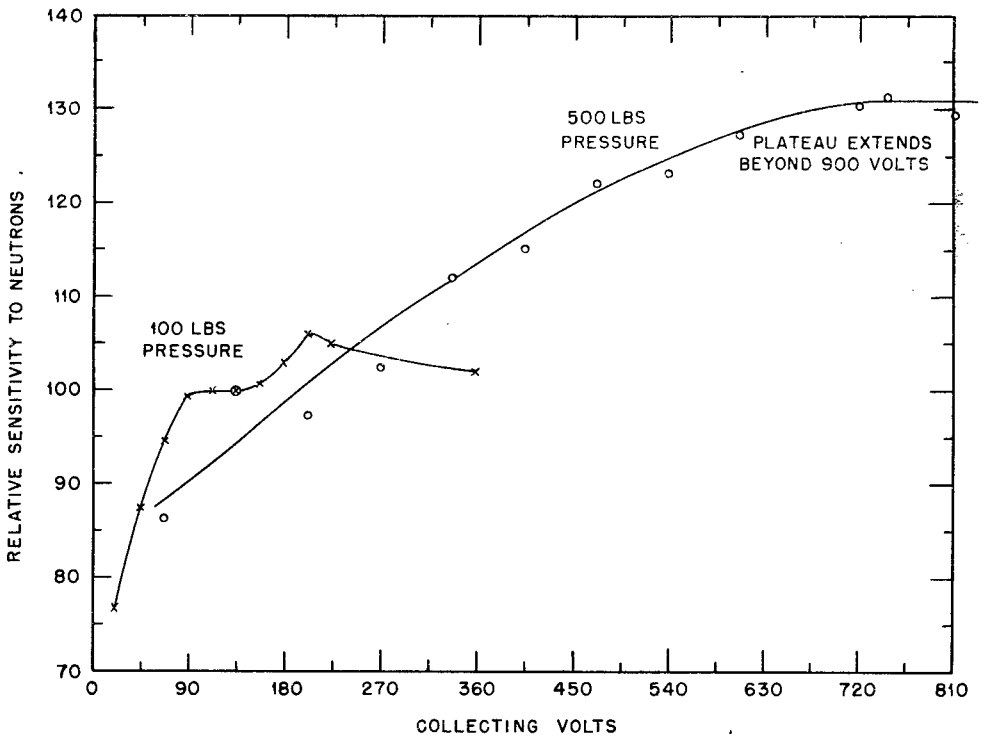

Figure 2

The present data agree with those of Wollan and Landsverk insofar as there is some pressure for which the ratio is equal to 8, and also insofar as there is a pressure range in which the ratio is nearly constant. But, unlike Wollan and Landsverk, we find that the pressure for which the ratio is 8 (25 pounds) does not fall into this range (400 to 600 pounds).

In practice, one wants both a high neutron-to-gamma sensitivity ratio, and high absolute sensitivities to both radiations. As can be seen from the three curves, these requirements cannot be met simultaneously. Arriving at a good compromise is the best that can be done. A pressure should be chosen at which neutron and gamma sensitivities are sufficiently high so that fractions of tolerance flux can be measured for both types of radiation (if this sensitivity is required). On the other hand, the sensitivity ratio should be maintained as high as possible.

The chambers that have been built here were filled to about 90 psi above atm. As is seen from the data in Section D (4), the gamma sensitivity at 90 pounds is such that about 330 micro "r" will produce a change in plate current of 25 microamperes in two minutes. This corresponds to a flux of 80 milli "r" in 8 hours, or 80% of tolerance flux. Smaller fluxes can be measured easily by choosing a smaller plate current interval and/or longer collection times. The neutron-to-gamma sensitivity ratio is 5 at 90 pounds. This means that neutron tolerance flux or less can also easily be measured (half as easily as gamma tolerance flux). Although the ratio of 5 is only half of the ideal ratio of 10, it will do in most cases. Usually one type of radiation is preponderant, and one usually knows which one. In case of doubt, the assumption that radiation is all neutrons will ensure staying on the safe side. The choice of 90 pounds pressure is furthermore to be recommended because the sensitivity will then not depend on the collection voltage, provided this voltage is of the order of 100 volts, as seen from the curve on the left of Figure 2. That means that a 90-volt or a 135-volt battery can be used, which helps in keeping the weight of the instrument within reasonable limits.

2. Theoretical Considerations

The qualitative behavior of the absolute and relative sensitivities of the pressure chamber can be explained along the following lines.

The ionization in the chamber is due to secondaries (e.g. Compton electrons, proton recoils) which are released both in the wall and within the gas. The number of secondaries from the wall is independent of the density of the gas. However, the number of secondaries released in the gas volume is proportional to the density.

The number of ions produced by each secondary in the chamber volume depends on what portion of the secondary's range is spent in that volume. If, at a given pressure, the secondary's range ends within the chamber, an increase in pressure cannot lead to an increase in ion collection from that single secondary. If, however, a secondary has a range large compared to the chamber dimensions, then an increase in pressure will result in creation of more ions within the chamber by this secondary.

Unfortunately, the contraction of ranges with increasing pressure cannot be utilized fully. Only those ions are measured that have been collected. With a constant collection field, the collecting efficiency will decrease as the pressure is raised, since the ion recombination rate is proportional to the second power of the gas density. Furthermore, the collecting efficiency will be worse for protons than it is for electrons, as protons produce a greater number of ions per unit path than electrons.

The linearity of curves 1 and 2 (Figure 1) at low pressures reflects the increase in secondaries produced. For very low pressures, contraction or ranges may also contribute to the initial rise of the curves, although there is no way of separating this effect from the former by inspecting these experimental data. Recombination of ions is responsible for the decrease in the slope of the curves as the pressure gets higher. In the case of neutrons this effect is more strongly pronounced and sets in at a lower pressure.

As a consequence, the relative neutron-to-gamma sensitivity goes down with increasing pressure. It is remarkable that the initial value of this ratio (ratio of slopes of curves at low pressure) being equal to 8, is very close to the factor 10 as theoretically predicted along Wollan's lines of reasoning (see Section C). That the decreasing slope of curve 1 is due to a decrease in collecting efficiency is confirmed by the curves of Figure 2. At high pressure, an increase of collecting voltage up to 700 volts leads to an increase in sensitivity, which can only mean that the recombination of ions is reduced. At low pressure, the ion collection reaches its maximum efficiency at about 200 volts.

F. Constructional Detail

The construction of the pressure chamber is illustrated in Figure 3 (assembly drawing) and Figure 4 (photographs). Since the drawing was made, an improved polystyrene plug has been inserted. The new plug is counterbored at the end that protrudes out of the chamber, in order to create a larger leakage path. At the other end of the plug a cylindrical extension has been added, again in order to cut down possible electrical leakage.

The high voltage electrode consists of a number 6 wire mesh cylinder seated inside a 1/8-inch paraffin layer. The paraffin is coated on the inside of the steely cylinder. It serves to insulate the high voltage electrode from the wall. A test showed that the reduction in chamber volume due to the insertion of the paraffin did not cut down on the sensitivity to neutrons, but did cut down somewhat (about 10%) on that to gamma rays, which actually serves to increase the relative neutron-to-gamma sensitivity.

A loose end of wire from the wire mesh is connected to a brass ring. This ring is mounted on a Lucite ring which fits against the edge of the paraffin layer. The collecting voltage is brought through the base plate by an insulated screw which sits on a rubber gasket. Soldered to the head of this screw is a bronze spring making contact to the brass ring. Thus, the steel cylinder is easily removed from the base plate, without any interference from the high voltage connection. Other details are obvious from the figures.

Six of these units, equipped with a pressure gauge, have been constructed. They were made to fit on the Rochester ion meter RM2.

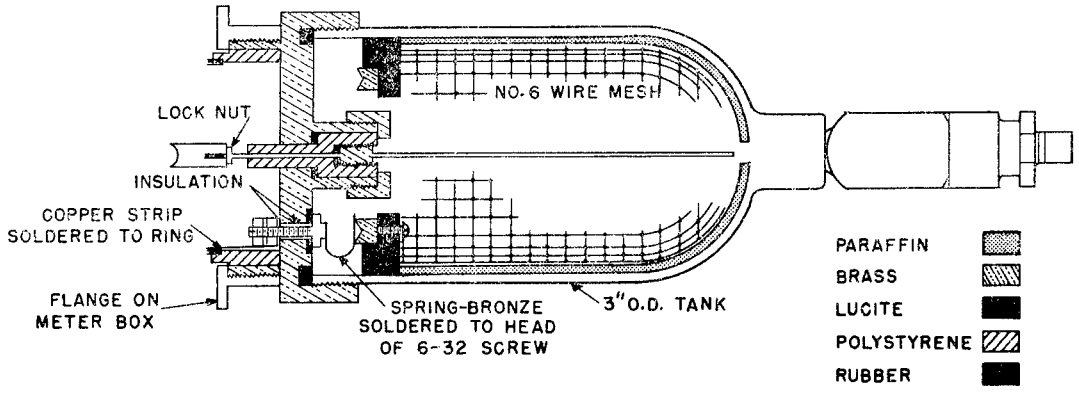

Figure 3

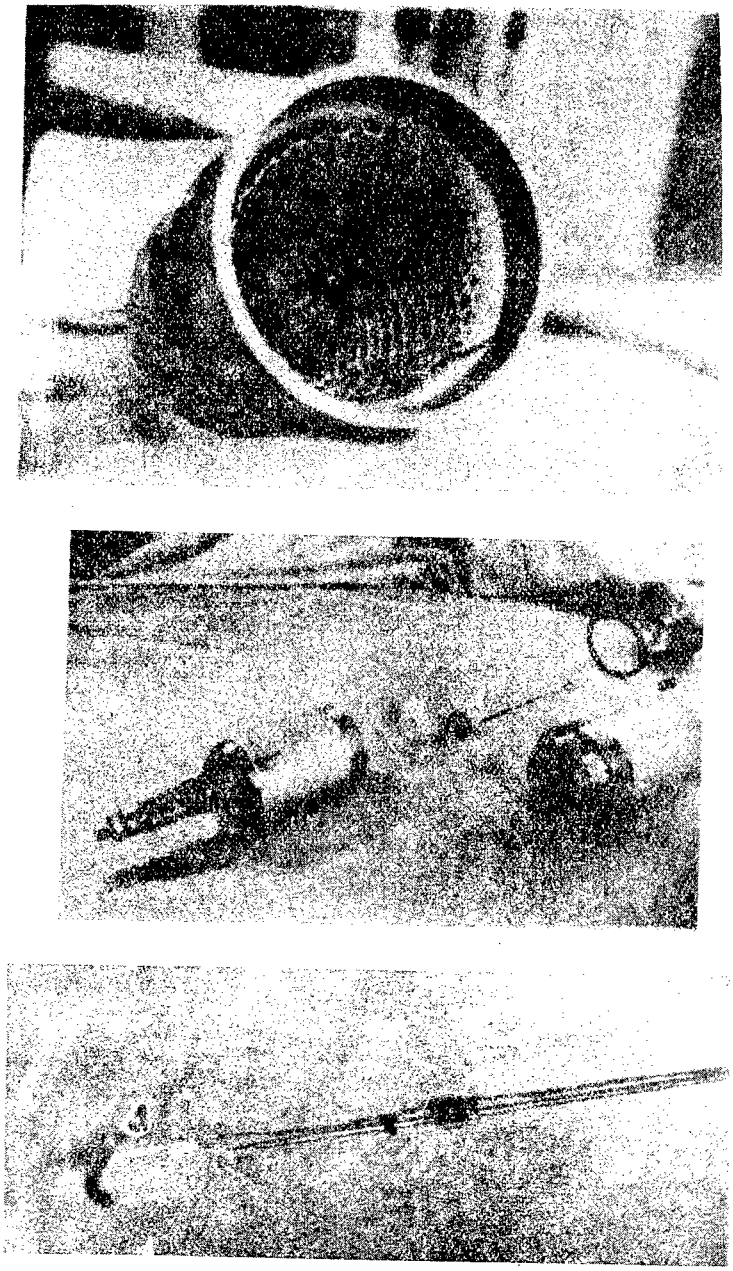

Figure 4